Possibilities and challenges of different experimental techniques for airflow characterisation in the air cavities of façades

Giancola, Emanuela; Sánchez, M. Nuria; Friedrich, Matthias; Larsen, Olena Kalyanova; Nocente, Alessandro; Avesani, Stefano ; Babich, Francesco; Goia, Francesco

Published in:
Journal of Facade Design and Engineering

DOI (link to publication from Publisher):
10.7480/jfde.2018.3.2470

Publication date:
2018

Document Version
Publisher's PDF, also known as Version of record

Possibilities and Challenges of Different Experimental Techniques for Airflow Characterisation in the Air Cavities of Façades

Emanuela Giancola[1*], M. Nuria Sánchez[1], Matthias Friedrich[2], Olena Kalyanova Larsen[3], Alessandro Nocente[4], Stefano Avesani[5], Francesco Babich[5], Francesco Goia[4]

* Corresponding author
1 Ciemat, Department of Energy, Energy Efficiency in Buildings Unit, Spain, emanuela.giancola@gmail.com
2 HafenCity University Hamburg, Germany
3 Aalborg University, Denmark
4 Norwegian University of Science and Technology, Norway
5 Eurac Research, Institute for Renewable Energy, Italy

Abstract

Ventilated façades are applied in both new and existing buildings. It has been claimed that these components help to reduce energy use in buildings and improve occupant comfort. However, their performance strongly depends on the airflow passing through the cavity. In order to characterise and to model the behaviour of the ventilation and its effectiveness, the components need to be tested in the laboratory, as well as under real dynamic weather conditions. Despite the steadily growing research in this area, there are few studies with conclusive results about the reliability of existing experimental procedures for characterisation of airflow in the ventilated cavities. The aim of this paper is to describe and review recent state of the art experimental assessments for the airflow characterisation in ventilated cavities. The paper starts with a short introduction on the potentialities and limitations of different experimental methodologies, and continues with a detailed classification and description of the most relevant monitoring techniques for airflow in air cavities of façades that have been developed in recent years.

Keywords

façade characterisation, experimental techniques, airflow monitoring, tracer gas, velocity profile, ultrasound, pressure difference, PIV, LDV, temperature profile & heat flux

DOI 10.7480/jfde.2018.3.2470

1 INTRODUCTION

A comfortable and hygienic indoor climate is one of the fundamental requirements expected of the building envelope. One method of coping with the need to reduce cooling loads through the envelope is to make use of a natural or mechanically induced airflow in the cavity of the façade (Lee, Sang, Yeo, & Kim, 2009). Even if there are many synonyms for the term 'ventilated façade' - such as active façade, double envelope, rain screen, or double skin façades (DSF) - which correspond (more or less) to different configurations, all of these terms refer to a building envelope system characterised by a ventilated layer. Currently, innovative building elements perform one or more of the several functions that a building envelope is required to do, but the assessment of their effectiveness is a complex task. The functions of façade systems to be tested are now more numerous (and more complex) than those traditionally assessed through conventional metrics (such as the U-value, or the g-value). In particular, when it comes to ventilated façades, the assessment of the performance is often connected to the assessment of the airflow rate. However, the on-site (and laboratory) characterisation of the airflow in a ventilated façade is not a trivial task. Although the European standard, EN 16211-2015 'Ventilation for buildings - Measurement of air flows on site – Methods', provides a description of the air flow methods and outlines how measurements are performed to achieve the stipulated measurement uncertainties, the implementation of these methods in a ventilated façade is not straightforward. There is therefore a clear need to define a robust and repeatable procedure for characterising the performance of ventilated façade, which goes hand in hand with the need to develop suitable facilities for research, development, and testing of façades (Cattarin et al., 2018; Goia, Schlemminger, & Gustavsen, 2017).

The performance of the ventilated façade has been evaluated both numerically and experimentally in multiple studies (López, Jensen, Heiselberg, Ruiz de Adana Santiago, 2012; Sanjuan, Suarez, Gonzalez, Pistono, & Blanco, 2011; Suarez, Joubert, Molina, & Sanchez, 2011). The experimental evaluations have been developed in different scenarios: real buildings, outdoor test cells, and indoor laboratories. Despite the differences between numerical predictions and experimental data, all results demonstrate a marked reduction in summer thermal loads due to the induced ventilation airflow. In-depth experimental analysis of this system will enable the updated model to better reproduce the façade energy savings and air quality conditions inside the building.

Following the classification proposed by Cattarin, Causone, Kindinis, and Pagliano (2016), the assessment of façade systems may be performed by means of three main types of test rig: outdoor real-scale facilities, outdoor test cells, and laboratory indoor facilities. The major constraints of field measurements are: a) the complexity of isolating a single variable (Serra, Zanghirella, & Perino, 2010); b) the difficulty in comparing the measured data with other available data sets, due to the unique architectural features of each real-scale building and the boundary conditions; c) the complexity of achieving a high level of instrumentation and control necessary for accurate performance assessment (Strachan & Vandaele, 2008). Instead, the tests carried out in controlled laboratory conditions give the possibility to carefully check the most influential parameters, such as ambient temperature, heating of the outer skin of the façade, relative humidity, and air velocity, as well as the possibility to test the influence of each parameter individually. Laboratory experiments are carried out under steady state or, where appropriate, dynamic boundary conditions with pre-defined test sequences. The effects of one or more meteorological conditions are sometimes imitated through dynamic programs, but these cannot fully reproduce the complex interactions of pure stochastic processes typical of real climate, as well as of some characteristics of the outdoor boundary conditions (such as, for example, the geometrical component of solar irradiation on the façade). Over the last decades, all types of mentioned experimental cells/facilities have contributed to the present state of the art in façade characterisation. However, different experimental methods for characterisation of the airflow in ventilated cavities can be used, depending on the geometry of the ventilated façade, peculiarities of the experimental cell, type of airflow, equipment at hand etc.

The determination of the airflow in the naturally ventilated cavities is a key and challenging issue. The influence of airflow, however, has not been studied to the same extent. The lack of an overview of different established procedures for collection of experimental data for naturally ventilated cavities (Dama, Angeli, & Kalyanova Larsen, 2017) is the main reason for the present state of the art. Measuring and predicting airflow are difficult tasks due to the stochastic nature of the wind. As reported by Perino et al. (2008), one of the main problems of uncertainty in the estimation of the airflow is determined by the wind conditions and by the thermal behaviour of the façade. An increase of airflow rate in the cavity will reduce the temperature difference between the exterior and the air in the cavity. As a result, the airflow rate will diminish. This 'self-regulating' interaction is reported by Saelens (2002).

The number of existing experimental methods for estimation of airflow rate in the built environment is limited to the following: tracer gas measurements, velocity profile method, and ultrasound measurement of velocity, as well as the use of models with measured pressure differences across the opening (Hitchin & Wilson, 1967) and the temperature profile along the ventilated cavities. Furthermore, the laser-based non-intrusive experimental techniques of Laser Doppler Velocimetry (LDV) and Particle Image Velocimetry (PIV) (Sánchez, Sanjuan, Suárez, & Heras, 2013) are applied to determine indoor airflow behaviour. The air change rate of naturally induced airflow is significantly different in occupied spaces compared to façade cavities. However, there are no experimental methods specifically developed for ventilated cavities, and thus the traditional ones for occupied spaces are used. The scope of this paper is therefore to raise awareness about this problem and call for comparative investigations on existing experimental techniques, with a particular focus on naturally ventilated cavities, as well as on the development of specific guidelines for this purpose.

2 CLASSIFICATION AND REVIEW OF EXISTING EXPERIMENTAL TECHNIQUES FOR AIRFLOW CHARACTERISATION IN THE AIR CAVITIES OF FAÇADES

The intention of this section is to provide the reader with a comprehensive understanding of the experimental techniques for airflow characterisation of ventilated cavities, their possibilities and limitations. The key features of each technique are summarised in Table 1 at the end of this section.

2.1 TRACER GAS MEASUREMENTS

Tracer gas measurements for determining airflow rates in buildings are frequently applied (Laussmann & Helm, 2011). There are three established tracer gas techniques that can be found in the literature: decay, constant concentration, and constant emission (Etheridge, 2011). Looking at the applicability of each of these techniques in ventilated cavities, a constant emission method is normally used, although there are a number of limitations that contribute to high uncertainty of the results obtained using this method. By recording the concentration of tracer gas in a defined volume (e.g. a room) and considering the background concentration, as well as the tracer gas supply, the air change rate can be calculated. The tracer gas is initially assumed to be equally distributed throughout the whole space. However, this assumption is limited in ventilated spaces as there will be a lower concentration near the fresh air supply and exhaust openings, and a higher concentration in the deeper part of the room (horizontal gradient) (Larsen, 2006). In contrast to naturally ventilated occupied spaces, the application of the tracer gas method with constant emission in a ventilated façade brings additional uncertainty to the experimental estimation of naturally induced airflow. In the first place, this is caused by the stochastic behaviour of the wind and therefore the irregular dilution of the tracer gas, but the uncertainty is further increased by the lack of research within the field. Until now, there have been no clear guidelines established with regard to the application of tracer gas methodology in ventilated façades, since the effect of positioning the emission source within the ventilated cavity, as well as the number and location of tracer gas dilution measurement points on measurement accuracy remain unknown.

Marques da Silva, Gomes, and Moret Rodrigues (2015) tested different positions for tracer gas emission and concentration sampling points. Overall, the results show no clear tendency, as the airflow in the cavity is highly dynamic. The knowledge about flow dynamics of cavities is low and therefore no preferable position was found. Kalyanova, Jensen, and Heiselberg (2007) found that tracer gas emission near the supply air opening of a cavity can cause a 'wash-out effect' where the gas is flushed out near the opening before it can mix with the cavity air, resulting in an inaccurate (too high) airflow rate. Other sources of inaccuracies are found due to reverse flow and recirculation effects. Nevertheless, the tracer gas method is one of the best available options, due to the lack of good alternatives, relatively simple installation of sensors, and minimal required instrumentation.

2.2 VELOCITY PROFILE

The measurement of the air velocity is a means by which to determine the airflow rates and to estimate the surface convective heat transfer coefficient. Both these two variables are very relevant for the calculation of the façade air cavity performances and therefore the direct measurement of the air velocity is of great interest. Nevertheless, the air velocity spatial differences can vary substantially in the three-dimensional field, depending on the air cavity geometry and on the airflow regime. Consequently, the air velocity field is difficult to characterise or generalise by physical or empirical equations for all façade air cavities. The air velocity profile method allows for the assessment of the façade air cavity performance through the measurement of the air velocity at some characteristic points.

2.2.1 Experimental setup

Different types of anemometers can be used for punctual determination of air velocity. These devices must be able to detect high frequency fluctuations in transient air flow. The hot-wire and the hot-sphere anemometer are the most frequently used instruments in façade-related applications (Belleri, Avantaggiato, & Lollini, 2017; López et al., 2012; Manz, Schaelin, & Simmler, 2004; Mateus, Pinto, & Graça, 2014; Park, Augenbroe, Messadi, Thitisawat, & Sadegh, 2004), mainly because of their fast responses and velocity range between 0-5 m/s. The definition of the experimental layout in terms of number and position of the anemometers across and along the air cavity is a trade-off between reducing their number, lowering the air channel obstruction, and increasing the measurement points to better appreciate the velocity variation. The sensors must be located at a reasonable distance from any obstruction. One further relevant factor to be considered in defining the experimental setup is the influence of the solar radiation on the temperature-based measurement principle (e.g. hot-sphere) as discussed by Jensen, Kalyanova, and Hyldgaard (2007). An example of experimental set-up in an outdoor test bench can be found in Kalyanova et al. (2007).

2.2.2 Main challenges encountered in design and operation

The main challenge in applying this method is the reduction of the cavity cross section due to the probes, cables, and fixing system, as well as deficiency of the method in detecting the direction of the air streams (upward or downward). Larsen (2006) performed a measurement of the velocity profile in a naturally ventilated, wide cavity, where it is documented that due to high velocities in the boundary layer, a large number of measurement points in the boundary layer are necessary in order to build an accurate velocity profile. Accordingly, the measurement accuracy becomes a trade-off between a number of measurement points and the disturbances that are introduced into the experimental domain. Furthermore, the presence of upward and downward air streams poses problems in the design of the experimental set-up. Jensen et al. (2007) investigated a method to determine the flow direction by using two hot sphere anemometers. However, determination of flow direction at one point is not enough for an accurate estimation of the whole cavity airflow, as in the case of two-directional flow occurrences. A second relevant challenge is the choice of probes features. The uncertainty of the hot-wire measurement system normally varies depending on the inverse of the velocity module. On the contrary, for naturally ventilated cavities, high accuracy at low velocity is requested.

Finally, the experimental layout must be designed starting from the specific façade geometry and expected airflow regime. Consequently, the design of a good experimental layout is very challenging as it would require the extensive use of CFD simulations.

2.2.3 Limitation of the experiment

The main limitation of the experiment is the need for a detailed analysis of the airflow characteristics, due to the high 3D variability of the air velocity field. Consequently, a punctual measurement of the air velocity carries very limited information on the air cavity airflow regime. As a result, both the number and the location of the sensors need to be optimised.

2.3 ULTRASOUND MEASUREMENT OF VELOCITY

The use of sound waves in the ultrasound range is a well-established technique for the measurement of (volumetric) flows in ducts and pipes and for the measurement of wind velocity (2D, 3D) in the field of environmental monitoring. Though the principles on which this measurement technique is based have been known for a long time (Suomi, 1957), the development of sensors for HVAC applications is rather recent (Strauss, Weinberg, & Kopel, 1996) with ongoing research activities in the field of device development (Raine, Aslam, Underwood, & Danaher, 2015).

This class of measurement techniques, which makes use of the interaction of (ultrasonic) sound waves with the moving fluid to determine the average velocity along the path of the sound wave (Cuerva & Sanz-Andrés, 2000) is primarily based on two alternative concepts, to which correspond two different devices: the Doppler effect ultrasonic flow meter and the transit time ultrasonic flow meter.

2.3.1 Doppler shift flow meter

These devices are based on the measurement of the frequency shift between a sound wave and its reflection caused by the particles in the flow. The flow rate is analytically determined, knowing the thermophysical properties and state properties, based on the Doppler effect equation, by processing the signals from the transmitter and the receiver. It is necessary that the fluid under analysis is able to reflect ultrasonic waves due to small bubbles of gas (in the case of a liquid) or the presence of eddies in the flow stream.

2.3.2 Transit time flow meter

These devices are based on the contemporary emission/reception of two identical sound waves between two couples of emitter/receiver, where one emitted/received soundwave travels downstream and the other upstream of the direction of the fluid flow. In the case of a still air mass, the transit time in each direction is identical, while under a flowing volume the downstream sound wall travels faster than the upstream one, and the difference between the two velocity values increases with the flow rate. The transmitter analytically calculates the average velocity of the flow rate based on the difference in the transit time across the two sound paths.

2.3.3 Main challenges encountered in design and operation

The use of ultrasonic principle for airflow monitoring presents several advantages: a) it can handle a very wide range of velocity, under different flow regimes; b) it is non-intrusive and does not influence the fluid flow; c) one sensor measures the average velocity across a section of the façade/duct, and multiple directions can be measured if more sensors are installed; d) because of the use of the difference between two velocity values, the procedure is independent from the temperature and pressure conditions of the fluid. When it comes to limitations and challenges, it is worth mentioning that the accuracy of this technique is reduced with very low air velocity. Accuracy is also reduced for cavities that are too deep or too thin, but the technique seems to be well suited to measuring airflows in cavities in the approximate range of 0.1m to 0.5m.

When more sensors are installed in the same cavity, and are close to each other, different frequencies for each sensor might be necessary to avoid incorrect readings. The implementation of this technique in a ventilated façade is not an established procedure and there may be challenges that are unknown at present, and which will be experienced only after several tests with this technique have been carried out.

2.3.4 Limitation of the experiment

The accuracy of this measurement method is relatively good and can be in the range of 2 -5% of the measured values. However, in the case of extremely low velocity (range of 10^{-2} m/s) the uncertainty can become far higher, and almost in the range of the measured values. Research activities are definitely necessary to deepen the applicability of this technique to façade systems due the poor literature in the field. Requirements in terms of developed flow regime are to be investigated, due the lack of standardised procedures for the application of ultrasonic sensors.

2.4 MEASURED PRESSURE DIFFERENCE

In theory, a pressure difference across an opening of naturally ventilated façade reflects the airflow rate induced by wind and buoyancy. More exactly, a relationship between the pressure difference and the airflow passing through the opening can be expressed as an equation (1) where Q is air flow (m^3/h), ΔP is pressure difference (Pa), and a, b are empirically obtained coefficients. Coefficients a and b depend on the shape of the opening itself and therefore the resistance that it initiates into the air passage.

$$Q = a \cdot \Delta P^b$$

This theory is used as a background for the pressure difference methodology for airflow measurement of naturally induced airflow, which is comparable to the measurement of the airflow in mechanically ventilated spaces using an orifice method. The method includes two stages: the calibration of the opening and the actual measurement. In contrast to the relatively accurate orifice method, little progress was made with regard to the pressure difference method, in terms of accuracy evaluation, as well as in terms of its practical application.

At present, there is only one known example of this method application. In Kalyanova et al. (2007) it is used in the full-scale outdoor test facility 'Cube', where the results of this method are found to be disappointing for the natural airflow, but relatively successful when the cavity is mechanically ventilated. The main finding of this work is that the method is very sensitive to the positioning of the surface pressure and reference measurement, to the fluctuations in wind direction and wind speed. Thus, further research is needed to establish a suitable methodology for the pressure difference measurement in a naturally ventilated cavity as it gives strong inspiration for finding a way to cope with the extremely high wind fluctuations and thereby fluctuations of the airflow.

2.5 PARTICLE IMAGE VELOCIMETRY (PIV)

PIV is an optical method of flow visualisation and quantification of instantaneous velocity fields, measuring two velocity components in an area of analysis by adding small tracer particles. Different suitable materials and particle generators are used. Seeding particles are selected to ensure acceptable flow tracking and adequate light scattering efficiency. However, determining optimal particle size is more critical in turbulent flows and high-speed gas flows since the particle's motion is more complex to treat. 2D-PIV has become a common technique used in research studies based on PIV, though a more complex PIV setup based on stereoscopic flow field analysis (Stereo-PIV) has been used increasingly in recent years (Sánchez, Giancola, Suárez, Blanco, & Heras, 2017). The latter enables the measurement of the out of plane velocity component. Currently, the new concept of volumetric velocimetry (TOMO PIV) enables the measurement of the three velocity components in a volume.

2.5.1 Experimental setup

- A constructed ventilated façade model is simplified but designed considering the basic structure of real ventilated façades with the three main components: an exterior layer creating open joints, an inner layer, and an air chamber created between both coatings. A heating mat system is installed and well-adhered to the outside of the outer layer.

- Laboratory indoor facilities:
  - A fully-equipped lab with a double cavity pulsed laser, charge-coupled device cameras generating sets of images downloaded onto a PC, a Laser Pulse Synchroniser acting as an external trigger to control the whole system, and a six jet atomiser which generates tracer particles.
  - Additionally, temperature sensors and an infrared thermographic camera are used to perform different temperature measurements.

2.5.2 Main challenges encountered in design and operation

The PIV technique requires a strong initial investment in human and financial resources. The equipment is sophisticated and quite expensive, as is its regular maintenance and upgrading. Additionally, laboratory personnel must be specialised in handling PIV equipment and its complex methodology. The design of the façade model presents multiple challenges. It is important to ensure the versatility and easy assembly of the model, dividing it into multiple components that can be easily exchanged.

Several challenges are faced because the experimental evaluation of the ventilated cavity is performed in laboratory conditions. Experimental limitations are mainly linked to the specific requirements of the PIV technique, the dimensions of the laboratory, and the reproduction of real environmental conditions. A major challenge of the experiment is to emulate the effect of incident solar radiation on the panels.

Regarding the operation of experimental PIV measurements, the limited size of the measurement area of the CCD cameras does not enable the capturing of the airflow evolution inside the ventilated camera in a single experimental run.

2.5.3 Limitation of the experiment

A major limitation of this technique is to simulate wind effect on airflow inside the ventilated cavity. Solar heat load effects are also critical with respect to façade performance. Solar radiation outdoor conditions are usually reproduced in the laboratory by using heating mats over the exterior layer.

2.6 LASER DOPPLER VELOCIMETRY (LDV)

The LDV or Laser Doppler Anemometry (LDA) is a laser-based optical method for velocity measurement in transparent or semi-transparent fluids. Invented by Yeh and Cummins (1964), it is based on the Doppler shift in a laser beam scattered by a particle (added as seeding or normally present in the flow).

2.6.1 Experimental setup

A monochromatic laser beam is divided in two in a Bragg cell, a device that uses the opto-acoustic effect to introduce a frequency shift in one of the beams. Each beam is then separated into three colours and each addressed to the probe. Here, a lens focuses the beams which collide in the measurement volume where the interference creates a series of fringes. When a particle crosses the fringes, it will scatter the light with a Doppler frequency proportional to its velocity in the three spatial directions. Since the frequency shift generates a known motion in the fringes, it is possible to resolve the sign of the velocity in each direction.

As with all the optical techniques, the LDV is not invasive (Moureh, Tapsoba, & Flick, 2009). A laser blade is not necessary, therefore the optical access is easier and there are no flare problems introduced by the blade sides (Wuibaut, Bois, El Hajem, Akhras, & Champagne, 2006).

2.6.2 Main challenges encountered in design and operation

The velocity is measured directly, with a linear response, and there is no need for calibration procedures. The accuracy is very high, due to the small dimension of the measurement volume, and the system has a better signal-to-noise ratio if compared to PIV since it does not require the analysis of artificially created images. Nevertheless, LDV measures one point at the time while PIV can reveal the global structure of the flow, which is useful in the research of flow mechanism. Special care needs to be taken regarding the accuracy of the traverse system for the placement of the probe and the optical setup (Zhang & Eisele, 1995). This assumes an even higher importance is given to 3D measurements, where one of the three couples of beams is focused by a second probe. In addition, the location of the measurement volume must be carefully evaluated, and it must be taken into account the possible influence that curved surfaces have on the reflection of the laser beam (Eisele, Zhang, Casey, Gulich & Schachenmann, 1997).

Typical application of LDV is in flow research such as aerodynamics of vehicles, water flow measurements, spray and combustion characterisation, as well as in automation, and lately in hemodynamics. The technique was successfully applied by Bhamjee, Nurick, and Madyira (2013) to the study of airflow in ventilated windows in cases of forced and natural flow.

2.7 TEMPERATURE PROFILE AND HEAT FLUX METHOD. REAL SCALE FACILITY

Real-scale facilities realise a large variety of full scale façade prototypes built on a large-scale test building (Marinosci, Semprini, & Morini, 2014) or in a real building (Fantucci, Marinosci, Serra, & Carbonaro, 2017; Giancola, Sanjuan, Blanco, & Heras, 2012). The enthalpy discharge linked to the airflow within the ventilated cavity directly affects the reduction of the heat flux across the inner wall; for this, the measure of the temperature profile is a means by which to quantify this effect. The data presented in literature indicates that for fixed weather conditions, to guarantee the lower thermal load entering the building, the measured temperature within the cavity must be the lower maximum value.

2.7.1 Experimental setup

In literature, the following variables are measured along the façade: air temperature in the middle of the ventilated cavity at different heights; surface temperature of the external layer and surface temperature of the insulated façade at different heights; velocity and direction of the wind next to the façade; heat fluxes at the interior and at the exterior surfaces of the inner mass wall; relative humidity and global radiation on the horizontal surface; global and infrared radiation on the façade surface; ambient temperature. Sensors are placed on the centreline of the façade at different heights above the floor. The surface temperature sensors are placed inside the ventilated cavity and are exposed to occasional handling as well as to climatic conditions. Consequently, open-wire thermocouples of cooper-constantan type (T) are used. The surface temperatures inside the ventilated cavity are measured using bare sensors covered with a reflecting tape to prevent possible errors due to surface-to-surface radiation heat fluxes. The heat flux through the internal mass wall is measured with plane fluxmeters. The heat flux is measured at the inside surface and at the exterior surface of the inner mass wall.

2.7.2 Main challenges encountered in design and operation

The main challenges encountered in design and operation are the accuracy of the sensors and the measurement chain, as the assumptions included in the monitoring aim affect the overall uncertainty of the performance indicators. Experiments carried out in real-scale facilities are usually designed to evaluate the overall energy performance of the building. In addition, real-scale facilities present many more limitations which restrict their field of applicability.

2.7.3 Limitation of the experiment

A major limitation is due to longer testing periods than steady-state laboratory tests. Real-scale facilities are exposed to the external environment conditions that affect material degradation for which they require continuous maintenance and care. Another limitation is the lack of a standardised procedure.

Technique	Physical principle	Application			Type of measurements	Intrusive		Measured Physical Quantity	Usual Accuracy	Technical complexity	Investment
		Real scale	Test Cell	Laboratory		Yes	No				
Tracer gas (Constant emission)	Conservation of mass (air and tracer gas)	X	X	X	Single points or volume	X		Concentration of tracer gas to obtain air ventilation rate	Low	Low	Low
Velocity Profile	Temperature-based measurement sensors	X	X	X	Single points	X		Air velocity	Low	Low	Low
Ultrasound a) Doppler shift flow meter b)Transit time flow meter	a) Frequency shift between sound wave and its reflection b) Transit time in fluid flow of identical sound waves upstream vs downstream	X	X	X	Plane		X	The interaction of ultrasonic sound waves with the moving fluid to obtain air velocity	Medium	Medium	Low
Pressure Difference	Relation between the pressure difference and the airflow passing through an opening		X	X	Single points	X		Air pressure difference to obtain airflow rate	Low	Low	Low
PIV	Cross-correlation between consecutive images of laser light scattered by tracer particles			X	Plane or volume		X	Particle images displacement over a given time interval between consecutive two laser pulses to obtain air velocity field	Very High	High	Extremely High
LDV	Doppler shift in a laser beam scattered by a particle	X[1]	X[1]	X	Single points		X	Doppler frequency of scattered light proportional to particles velocity	High	High	Extremely High

>>>

Temperature Profile and Heat Flux method	Enthalpy discharge	X	X	X		X		Ambient and surface Temperature Heat Flux Relative Humidity Global Radiation on the horizontal surface Global and Infrared Radiation on the facade surface	Low	Low	Low

TABLE 1 Key features of each experimental techniques for airflow characterization of ventilated cavities

[1] *If the amount of naturally occurring seeding particle (i.e. dust) is sufficient*

3 CONCLUSIONS

The experimental evaluation of the airflow rates in ventilated façades is proven not to be a straightforward task. Until now, the experimental methods developed specifically for characterising ventilation in buildings and airflow in ducts were applied for measurements on ventilated façades. This is one of the reasons why there are few studies with conclusive results about the reliability of existing experimental procedures for the characterisation of airflow in the ventilated cavities. There is, therefore, a need to raise awareness on the lack of knowledge and robust procedures to assess the airflow in a ventilated façade. This paper has therefore the intention of stimulating:

- further testing of existing methods in order to evaluate their accuracy for application with ventilated cavities;
- the development of common guidelines and generally acknowledged measurement procedures for application with ventilated façades; and
- the development of new methods suitable for application with ventilated cavities.

In this paper, a description and a review of the recent state of the art of the experimental assessments for the airflow characterisation in ventilated cavities was presented. The classification is based on laboratory tests, as well as under real dynamic weather conditions. The tests carried out in a controlled laboratory give the possibility to carefully check all the most influential parameters. The number of existing experimental methods for the estimation of airflow rate in the built environment is limited to the following: tracer gas measurements, velocity profile method, and ultrasound measurement of velocity, as well as the use of models with measured pressure differences and the temperature profile along the ventilated cavities. Furthermore, the laser-based non-intrusive experimental techniques of Laser Doppler Velocimetry (LDV) and Particle Image Velocimetry (PIV) are applied to determine indoor airflow behaviour. Potentialities and limitations as well as a detailed classification and description of such monitoring techniques for airflow in façades air cavities have been reported.

Considering the applicability of each of the tracer gas measurement techniques in ventilated cavities, a constant emission method is normally used. Until now, no clear guidelines have been established with regard to the application of tracer gas methodology in ventilated façades, as the effect of positioning the emission source within the ventilated cavity, as well as number and location of tracer gas dilution measurement points on measurement accuracy remain unknown. Overall, the results show no clear tendency as the airflow in the cavity is highly dynamic. The measurement of the air velocity is a means by which to determine the airflow rates and to estimate the surface convective heat transfer coefficient.

The air velocity profile method allows the assessment of the façade air cavity performance from the measurement of the air velocity at some characteristic points. The main limitation of the experiment is the need for a detailed analysis of the airflow characteristics, especially in airflows with high 3D variability of the air velocity field. The use of the ultrasonic principle for airflow monitoring presents several advantages, for example: it's non-intrusive and does not influence the fluid flow. The accuracy of this measurement method is relatively good and can be in the range of 2 - 5% of the measured values. Research activities are definitely necessary to advance in their effective implementation to façade systems, paying special attention to the requirements in terms of developed flow regime. Currently, the results of pressure difference method application to a ventilated cavity are successful in mechanically ventilated cavities but differ considerably in natural airflows.

The main finding of this work is that the method is very sensitive to the positioning of the surface pressure and reference measurement, and to the fluctuations in wind direction and wind speed. Thus, further research is needed to establish a suitable methodology for the pressure difference measurement in a naturally ventilated cavity, as it gives strong inspiration for finding a way to cope with the extremely high wind fluctuations and thereby fluctuations of the airflow. A major limitation in real-scale facilities is the testing time, longer than normal testing periods in laboratory. Also, resulting from its environmental exposure, material rapidly becomes degraded and ongoing maintenance is required.

All previous techniques have the common drawback of measuring over single points or single sections instead of a field or a volume to characterise the three-dimensional behaviour of the air velocity field. Consequently, previous measurement methodologies need to be further developed, determining optimal points of measurement set up to balance low intrusiveness in airflow with adequate spatial resolution.

The non-intrusive ultrasound PIV on the contrary, allows detailed analysis of the airflow variability. However, the important initial financial investment and the technical complexity might be an obstacle to their widespread application. A major limitation of this technique is the simulation of wind effect on airflow inside the ventilated cavity. Solar heat load effects are also critical with respect to façade performance.

Acknowledgements
The authors acknowledge the networking opportunities given by the Cost Action TU1403 "Adaptive Facades Network".

References

Belleri, A., Avantaggiato, M., & Lollini, R. (2017). Ventilative Cooling in Shopping Centers' Retrofit: The Mercado Del Val Case Study. *Energy Procedia 111*, pp. 669-677

Bhamjee, M., Nurick, A., & Madyira, D. M. (2013). An experimentally validated mathematical and CFD model of a supply air window: Forced and natural flow. *Energy and Buildings 57*, pp.289-301

Cattarin, G., Causone, F., Kindinis, A., & Pagliano, L. (2016). Outdoor test cells for building envelope experimental characterisation - A literature review, *Renewable and Sustainable Energy Reviews 54*, pp.606-625

Cattarin, G., Pagliano, L., Causone, F., Kindinis, A., Goia, F., Carlucci, S., & Schlemminger, C. (2018). Empirical validation and local sensitivity analysis of a lumped-parameter thermal model of an outdoor test cell. *Building and Environment 130*, pp. 151–161

Cuerva, A., & Sanz-Andrés, A. (2000). On sonic anemometer measurement theory. *Journal of Wind Engineering and Industrial Aerodynamics 88* (1), pp.25-55

Dama, A., Angeli, D., & Kalyanova Larsen, O. (2017). Naturally ventilated double-skin façade in modeling and experiments. *Energy and Buildings 144*, pp.17–29

Eisele, K., Zhang, Z., Casey, M. V., Gulich, J., & Schachenmann, A. (1997). Flow analysis in a pump diffuser—part 1: LDA and PTV measurements of the unsteady flow. *Journal of Fluids Engineering 119(4)*, pp.968-977

Etheridge, D. (2011). *Natural Ventilation of Buildings: Theory, Measurement, and Design*. Hoboken, New Jersey: John Wiley & Sons, pp. 428

EUROPEAN STANDARD, (2015). Ventilation for buildings - Measurement of air flows on site – Methods. NS-EN 16211, European Committee for Standardization, Brussels, Belgium

Fantucci, S., Marinosci, C., Serra, V., & Carbonaro, C. (2017). Thermal Performance Assessment of an Opaque Ventilated Façade in the Summer Period: Calibration of a Simulation Model through in-field Measurements. *Energy Procedia 111*, pp.619-628

Giancola, E., Sanjuan, C., Blanco, E., & Heras, M. R. (2012). Experimental assessment and modelling of the performance of an open joint ventilated façade during actual operating conditions in Mediterranean climate, *Energy and Buildings 54*, pp.363-375

Goia, F., Schlemminger, C., & Gustavsen, A. (2017). The ZEB Test Cell Laboratory. A facility for characterization of building envelope systems under real outdoor conditions. *Energy Procedia 132*, pp. 531-536

Hitchin, E. R., & Wilson, C. B. (1967). A Review of Experimental Techniques for the Investigation of Natural Ventilation in Buildings. *Building Science 2*, pp.59-82

Jensen, R. L., Kalyanova, O., & Hyldgaard, C. E. (2007). On the use of hot-sphere anemometers in a highly transient flow in a double-skin façade. *Proceedings of Roomvent 2007. FINVAC ry*, Helsinki, Finland

Kalyanova, O., Jensen, R. L., & Heiselberg, P. (2007) Measurement of air flow rate in a naturally ventilated double skin façade. *Proceedings of Roomvent 2007. FINVAC ry*, Helsinki, Finland

Larsen, T. S. (2006). *Natural Ventilation Driven by Wind and Temperature Difference.* (DCE Thesis). Department of Civil Engineering, Aalborg University, Aalborg, Denmark

Laussmann, D., & Helm, D. (2011). Air Change Measurements Using Tracer Gases. In Mazzeo, N. (eds.) *Chemistry, Emission Control, Radioactive Pollution and Indoor Air Quality*, pp. 365-406. InTechOpen, Rijeka, Croatia doi: 10.5772/18600

Lee, S., Sang, H. P., Yeo, M. S., & Kim, K. W. (2009). An experimental study on airflow in the cavity of a ventilated roof. *Building and Environment 44*, pp.1431–1439

López, F. P., Jensen, R. L., Heiselberg, P., & Ruiz de Adana Santiago, M. (2012). Experimental analysis and model validation of an opaque ventilated facade. *Building and Environment 56*, pp. 265-275

Manz, H., Schaelin, A., & Simmler, H. (2004). Airflow patterns and thermal behavior of mechanically ventilated glass double façades. *Building and Environment 39 (9)*, pp. 1023-1033

Marinosci, C., Semprini, G., & Morini, G.L. (2014). Experimental analysis of the summer thermal performances of a naturally ventilated rainscreen façade building. *Energy and Buildings 72*, pp.280-287

Marques da Silva, F., Gomes, M. G., & Moret Rodrigues, A. (2015). Measuring and estimating airflow in naturally ventilated double skin facades. *Building and Environment 87*, pp.292-301

Mateus, N. M., Pinto, A., & Graça, G. Cd. (2014). Validation of EnergyPlus thermal simulation of a double skin naturally and mechanically ventilated test cell. *Energy and Buildings 75(0)*, pp.511-522

Moureh, J., Tapsoba, M., & Flick, D. (2009). Airflow in a slot-ventilated enclosure partially filled with porous boxes: Part I–measurements and simulations in the clear region. *Computers & Fluids 38(2)*, pp.194-205

Perino, M., Serra, V., Zanghirella, F., Issoglio, R., Marques da Silva, F., & Gomes, M.G. (2008) Performance evaluation of advanced integrated façades in laboratory facilities. *Proceedings of 29th International AIVC Conference*, Kyoto, Japan

Park, C. S., Augenbroe, G., Messadi, T., Thitisawat, M., & Sadegh, N. (2004). Calibration of a lumped simulation model for double-skin façade systems. *Energy and Buildings 36*, pp. 1117-1130

Raine, A.B., Aslam, N., Underwood, C.P., & Danaher, S. (2015). Development of an Ultrasonic Airflow Measurement Device for Ducted Air. *Sensors 15*, pp.10705-10722

Saelens, D. (2002). *Energy performance assessment of single storey Multiple-Skin Facades.* (Doctoral Thesis) Laboratory for Building Physics, Department of Civil engineering, Catholic University, Leuven, Belgium

Sánchez, M. N., Sanjuan, C., Suárez, M. J., & Heras, M. R. (2013). Experimental assessment of the performance of open joint ventilated façades with buoyancy-driven airflow. *Solar Energy 91*, pp.131-144

Sánchez, M. N., Giancola, E., Suárez, M. J., Blanco, E., & Heras, M. R. (2017). Experimental evaluation of the airflow behaviour in horizontal and vertical Open Joint Ventilated Facades using Stereo-PIV. *Renewable Energy 109*, pp.613-623

Sanjuan, C., Suarez, M. J., Gonzalez, M., Pistono, J., & Blanco, E. (2011). Energy performance of an open-joint ventilated façade compared with a conventional sealed cavity façade, *Solar Energy 85 (9)*, pp.1851-1863

Serra, V., Zanghirella, F., & Perino, M. (2010). Experimental evaluation of a climate façade: energy efficiency and thermal comfort performance, *Energy and Buildings 42*, pp.50-62

Strachan, P.A., & Vandaele, L. (2008). Case studies of outdoor testing and analysis of building components. *Building and Environment 43*, pp. 129–42

Strauss, J., Weinberg, H., Kopel, Z. (1996). *U.S. Patent 5,583,301*: Ultrasound Air Velocity Detector for HVAC ducts and method therefor

Suarez, C., Joubert, P., Molina, J. L., & Sanchez, F. J. (2011). Heat transfer and mass flow correlations for ventilated facades, *Energy and Buildings* 43, pp.3696-3703

Suomi, V.E. (1957). *Sonic Anemometer, Exploring the Atmosphere's First Mile, Vol. 1*. New York: Pergamon Press, pp.356–366

Wuibaut, G., Bois, G., El Hajem, M., Akhras, A., & Champagne, J. (2006). Optical PIV and LDV comparisons of internal flow investigations in SHF impeller. *International Journal of Rotating Machinery, vol. 2006*

Yeh, Y., & Cummins, H. (1964). Localized fluid flow measurements with an He–Ne laser spectrometer. *Applied Physics Letters,* 10(4), pp.176–178

Zhang, Z., & Eisele, K. (1995). Off-axis alignment of an LDA-probe and the effect of astigmatism on measurements. *Experiments in fluids 19(2),* pp.89-94